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THE IONIZATION MECHANISM OF THE "LINER" GALAXIES PICTOR A AND PKS 1718−65

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ABSTRACT

High-resolution optical spectra are presented of two galaxies with Liner (low-ionization nuclear emission-line region) nuclei, Pictor A and PKS 1718−65. Both emit strong [O III] λ4363, but the ratio of this line with respect to [O III] λ5007 is so high that it must be influenced by high electron density. Hence, these lines cannot be used to measure the electron density and test shock-heating versus photoionization models of Liners in a straightforward way. Nonetheless, Pictor A is shown to have a strong featureless optical continuum and He II λ4686 emission, making it the best case to date of a power-law photoionized Liner. The spectrum of PKS 1718−65 shows neither of these features, and thus is more like that of the prototype Liner, NGC 1052. If the Liners in such galaxies as these are photoionized rather than shock-excited, the ionizing spectrum must be more like a blackbody than a power-law spectrum.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — radiation mechanisms

I. INTRODUCTION

The emission-line gas in the class of low-ionization active galaxies now known by the acronym Liners (low-ionization nuclear emission-line regions [Heckman 1980]) was originally thought to be excited by shock heating, because available shock-heating models could fit the observed spectra. Ferland and Netzer (1982) and Halpern and Steiner (1983) have since shown that the strongest emission lines in the observed spectra can also be reproduced by power-law photoionization models with very low values of the ionization parameter. The principal discriminants at optical wavelengths between these two models are that (1) the [O III] λ4363/λ5007 intensity ratio should always be large for shock-heated gas, because of high electron temperatures, but in the low-density limit should be quite small for photoionized gas, and (2) the power-law photoionization models predict the He II λ4686/Hβ intensity ratio to be high while the shock models generally do not. The hope of applying the first of these discriminants has led to several reassessments of the λ4363/λ5007 ratio in the prototype Liner NGC 1052 (Keel and Miller 1983; Rose and Tripicco 1983), with the result that this ratio is now thought to be considerably smaller than was originally claimed. However, the question of the general importance of shock heating among this class of galaxies is still very much open.

In the course of a high-resolution study of the emission-line spectra of a number of active galactic nuclei, we observed two galaxies, Pictor A and PKS 1718−65, which have classical Liner spectra. A detailed look at their spectra sheds some additional light on the shock versus photoionization question.

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II. OBSERVATIONS

High-resolution (0.56 Å at 5000 Å) spectra of Pictor A and PKS 1718−65 were obtained with a 40 mm silicon intensified target (SIT) Vidicon detector attached to the echelle spectrograph at the Cassegrain focus of the Cerro Tololo Inter-American Observatory 4 m telescope. The wavelength coverage was approximately 4000–8000 Å. A log of these observations is found in Table 1. A full description of the

TABLE 1

OBSERVING LOG

Date (UT)	Resolution (Å)	Slit-Center Position[a]	Slit P.A.[b]	Exposure Time (min)
Pictor A:				
1981 Jan 2	15	nucleus	0°	6
1981 Jan 2	15	2.5W	0	10
1981 Jan 2	15	5W	0	40
1981 Jan 2	15	2.5E	0	10
1981 Jan 2	15	5E	0	20
1981 Jan 3	15	nucleus	90	4
1981 Jan 3	15	3.3S	90	25
1981 Jan 3	15	5S	90	15
1981 Jan 3	15	3.3N	90	15
1981 Jan 4	2.5	nucleus	90	30
1981 Jan 4	2.5	nucleus	0	15
1981 Jan 4	2.5	2.5W	0	30
1981 Jan 4	2.5	5W	0	75
1981 Nov 2	0.5 (echelle)	nucleus	90	75
1981 Nov 3	0.5 (echelle)	nucleus	90	130
PKS 1718−65:				
1981 Jul 8	0.5 (echelle)	nucleus	90	180
1983 Feb 18	15	nucleus	90	20

NOTE.—All observations made with CTIO 4 m telescope, using Ritchey-Chrétien spectrograph except when "echelle" is noted.
[a] Offset from nucleus in arcsec.
[b] Position angle.

instrumental configuration is given by Atwood, Baldwin, and Carswell (1982).

Lower resolution SIT Vidicon spectra were obtained of the two galaxies with the 4 m telescope and Ritchey-Chrétien Cassegrain spectrograph (see Table 1 for details). For Pictor A, a grid of low-resolution off-nuclear spectra were taken with the same instrument to study the extended ionized gas associated with this object.

III. RESULTS

a) *Pictor A*

This N (or D) galaxy is associated with a strong double-lobed radio source, a compact nuclear radio source, and a strong source of hard X-rays, and also has infrared colors characteristic of a power-law spectrum (Christiansen *et al.* 1977; Marshall *et al.* 1979; Glass 1981; Ward *et al.* 1982). It therefore obviously contains a possible source of ionizing photons. Danziger, Fosbury, and Penston (1977), in a study of its optical spectrum, found emission-line widths of many hundreds of km s^{-1} and pointed out many similarities to the relative emission-line intensities found in supernova remnants, leading them to suggest that shock heating might be important. At low resolution the spectrum of Pictor A is extremely similar to that of NGC 1052, except that the optical nuclear continuum of Pictor A is blue and relatively featureless.

Our echelle spectra show the forbidden emission lines to

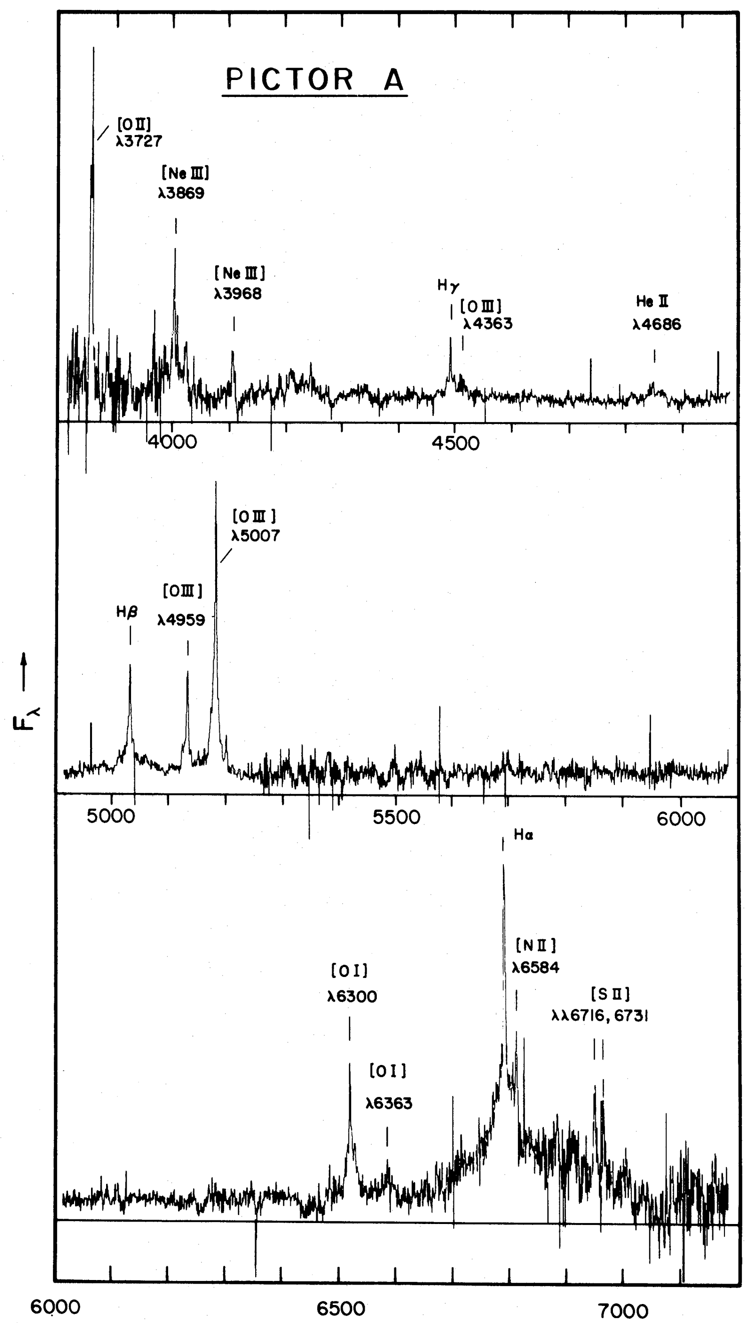

FIG. 1.—Echelle spectrum of Pictor A

have narrow cores (140 km s^{-1} FWHM) set on top of broad asymmetric wings (850 km s^{-1} FWHM) (see Figs. 1 and 2). Narrow-band SIT Vidicon direct images taken by Baldwin and Campusano (unpublished) show a "northwest knot" of gas with strong [O III] λ5007 located about 5″ arcsec northwest of the nucleus of Pictor A; the 2.5 Å resolution spectra we obtained show that at least in this direction the broader component of the [O III] λλ4959, 5007 lines is confined to the nucleus, while the narrow component is more extended. A grid of lower dispersion spectra shows that the nucleus of Pictor A is surrounded by emission-line gas out to a radius of about 7″. In the south and east quadrants the ionization level falls off until only [O II] λ3727 is detectable (λ3727/λ5007 > 3) at the outer edges, but in the northwest knot the gas maintains about the same λ3727/λ5007 ratio as is found in the narrow component of the nuclear emission lines (although there is some hint that Hβ is relatively weaker than in the nucleus).

Returning to our echelle spectrum of the nucleus, the Balmer-line profiles resemble those of the forbidden lines, with a narrow core atop a broader base. However, as first noticed by Danziger, Fosbury, and Penston (1977), a third, very broad component (FWZI ∼ 20,000 km s^{-1}) that has no counterpart in the forbidden lines is strongly present at Hα. This latter

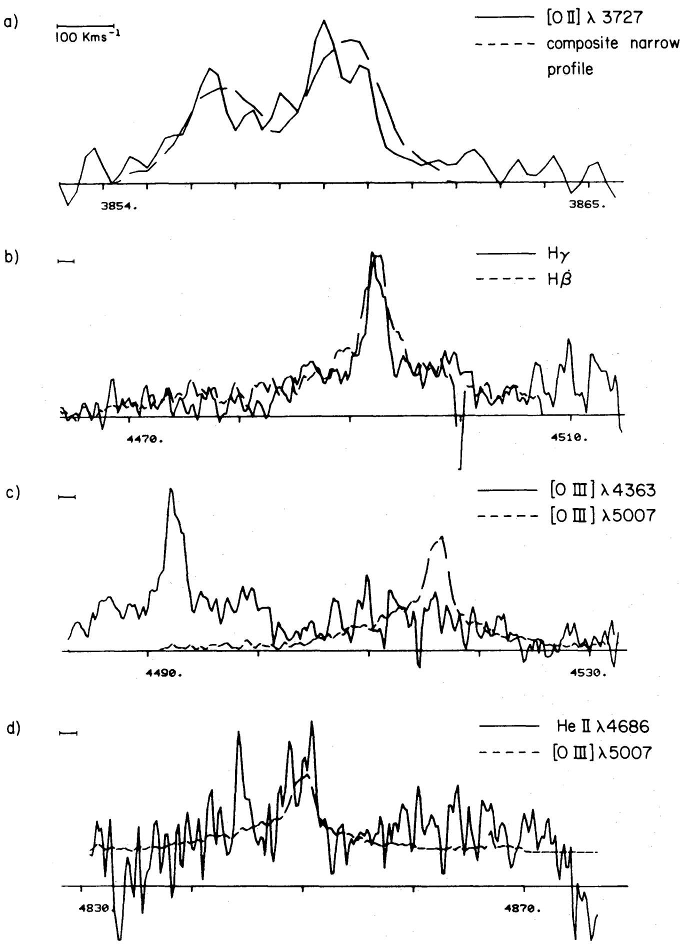

FIG. 2.—Comparison of the profiles of some important emission lines in the echelle spectrum of Pictor A. For the fit to [O II] λ3727, the intensity ratio $I(\lambda3726)/I(\lambda3729)$ has been set at the low-density limit. A bar 100 km s^{-1} long is shown to the upper left of each profile. The instrumental resolution is about 35 km s^{-1}.

component, which preseumably arises in gas with an electron density in excess of 10^8 cm^{-3}, is only weakly present at Hβ, implying a decrement considerably larger than the value of 3.6 measured for the narrow line cores. The very broad emission is too weak in the other permitted lines to be detected with confidence. The centroid of the very broad Hα component is noticeably redshifted with respect to the narrow core, and in many ways resembles the very broad Hα component observed in another Liner galaxy, NGC 7213 (Phillips 1979; Filippenko and Halpern 1984). In analogy with Osterbrock's (1981) scheme for Seyfert galaxies, the nuclei of Pictor A and NGC 7213 might best be classified as Liner 1.8.

We defined a standard narrow component profile by adding together the λ5007, λ4959, and Hβ profiles with 3:1:1 weighting and then subtracting off the underlying broad components. This standard profile was then fitted to the narrow core of each of the emission lines, yielding the relative narrow-component intensities listed in Table 2. In addition, [Ne V] λ3426 was detected on a low-resolution spectrum. The stronger lines indicate an excitation level of $\langle E \rangle = 0.29$, (3727/5007) = 0.49 in the BPT system (Baldwin, Phillips, and Terlevich 1981), which is very similar to that of NGC 1052. The individual lines all have the same shape as the standard profiles (to within the errors of the fairly noisy data). The [O II] λ3727 doublet is double-peaked and clearly broader than a single profile, and gave a best fit with the λ3726/λ3729 ratio at the low-density limit, $N_e < 200$ cm^{-3}. The [S II] λλ6716, 6731 doublet ratio (1:1) implies $N_e \sim 600$ cm^{-3}.

In this narrow-line system, [O III] λ4363 is quite weak (λ4363/λ5007 < 0.04), whereas He II λ4686 is reasonably strong. These are the characteristics of photoionized, rather than shock-heated, gas. Reference to Table 3 and to Figure 1 of Ferland and Netzer (1982) shows a good match to their model of a low-density, photoionized gas cloud with 0.3 times the solar metal abundances and an ionization parameter $U \sim 10^{-3.5}$. The observed intensity ratios from the gas in the knot to the northwest of the nucleus are also easily explained by this same model (with lower density compensating for the larger distance from the ionizing source). The gas to the south and east that shows only λ3727 emission is presumably at still lower U (and hence may be at higher density and/or greater true distance from the nucleus than the northwest knot) or perhaps is photoionized by some other source of radiation such as hot stars.

While the evidence points to photoionization of the narrowest-line component in the nucleus, and this picture can be nicely extended to include the outlying gas, the situation is ambiguous for the gas producing the broader two components of the emission lines. Relative intensities for the intermediate-width bases of the forbidden and permitted lines are listed in Table 2. The principal differences from the intensity ratios observed for the narrow cores are that λ3727/λ5007 is much lower, and that λ4363/λ5007 is large. (The broad emission bump that we identify with the [O III] λ4363 line is clearly detected in two orders each of two independent echelle spectra, and the underlying galaxy spectrum is too weak to confuse the issue. Moreover, careful fitting to the Hγ profile of the very broad wings seen at Hβ and Hα cannot account for this feature.) To within the limits of the signal-to-noise ratio of our spectrum, the λ4363 line has nearly the same width and profile as the base of λ5007 (Fig. 2). The intensity ratio of this component is considerably higher than is predicted by photoionization models, and even shock-heated models (cf. Shull and

TABLE 2

RELATIVE EMISSION-LINE INTENSITIES FOR PICTOR A

Line	Nucleus				Off-Nucleus		Power-Law Photoionization Model[b]
	Total Measured	Narrow Core[a]	Broad Base[a]	Very Broad Wings[a]	NW Knot	SE	
[Ne v] λ3426	0.20	...	...	...	...	...	...
[O II] λ3727	0.84	6.7	<3	...	7.0	3.0	6.4
[Ne III] λ3869	...	0.8:	...	...	<1.0	...	...
Hδ λ4101	...	0.3:	...	...	...	...	...
Hγ λ4340 }	0.44	0.49	0.4	...	...	...	0.47
[O III] λ4363 }		<0.1	0.21	...	...	...	0.025
He II λ4686	0.25	0.17	...	0.3?	...	...	0.17
Hβ λ4861	1.0	1.0	1.0	1.0	1.0:	<1.0	1.0
[O III] λ4959	0.55	0.97	1.0	...	3.5	...	0.72
[O III] λ5007	1.64	2.7	3.0	...	9.0	<1.0	2.2
[O I] λ6300	0.92	1.2	1.9	...	...	...	0.96
Hα λ6563 }	9.8	3.6	4.6	7.8	...	...	3.1
[N II] λ6584 }		1.:	...	...	...	...	1.6
[S II] λ6716	0.25	0.95	...	...	...	... }	2.5
[S II] λ6731	0.21	0.97	...	...	...	... }	
$F(H\beta)$ (ergs cm^{-2} s^{-1})	2.47×10^{-14}	3.0×10^{-15}	1.1×10^{-14}	2.3×10^{-14}	...	...	...
(λ3727/λ5007)	...	0.49	...	...	...	...	0.50
$\langle E \rangle$	...	0.29	...	...	...	...	0.31

[a] The intensity measurements for the individual components of the nuclear emission lines are obtained through a profile-fitting technique which, in the case of the "very broad wings" component, takes account of the extended red tail seen on the Hα profile, although this tail is blended with [O III] and is therefore unmeasurable in the case of Hβ. For this reason, the sum of the Hβ flux from the three components exceeds the "total measured" flux, which is just the flux that could be measured directly in unblended parts of the line profiles.

[b] Ferland and Netzer 1982.

McKee 1979), indicating that a moderately high electron density ($N_e \sim 10^5$–10^7 cm^{-3}) is present. At this N_e, the observations can be fitted equally well by photoionization models (with $U > 10^{-1}$) or by the shock-heated models.

Approximate relative intensities for the very broad components of Hα and Hβ are also given in Table 2. As mentioned previously, the Hα/Hβ ratio in this system is significantly greater than in the narrow cores. There is also a hint of this very broad component in the He II λ4686 line at about $\frac{1}{3}$ the intensity of the similar Hβ feature. If strong He II emission in this component can be confirmed, it would strongly suggest that *all* of the emission-line gas in the nucleus of Pictor A is photoionized by a power-law-like source of radiation.

TABLE 3

RELATIVE EMISSION-LINE INTENSITIES FOR PKS 1718−65

Line	Nucleus
[O II] λ3727	2.9
[Ne III] λ3869	...
Hδ λ4101	...
Hγ λ4340	0.25
[O III] λ4363	0.24
He II λ4686	<0.1
Hβ λ4861	1.0
[O III] λ4959	0.60
[O III] λ5007	1.8
[O I] λ6300	2.3
Hα λ6563	4.4
[N II] λ6584	3.1
[S II] λ6716 }	2.3
[S II] λ6731 }	
$F(H\beta)$ (ergs cm^{-2} s^{-1})[a]	2.3×10^{-14}
λ3727/λ5007	0.39
$\langle E \rangle$	0.29

[a] Measured from low-dispersion wide-slit (~6") spectra.

b) PKS 1718−65

This is a peculiar, nearly face-on, early-type spiral galaxy with an unusually large fraction of its mass (6%) in the form of H I (Fosbury *et al.* 1977). PKS 1718−65 has not been detected in X-ray complete samples, and Fosbury *et al.* (1977) could find no sign of an optical power-law continuum mixed in with the spectrum of the underlying galaxy, suggesting that the level of nuclear activity in this galaxy is lower than in Pictor A. Nevertheless, PKS 1718−65 is a strong flat-spectrum radio source.

The emission-line profiles of PKS 1718−65 seem to have the same composite nature as those of Pictor A, with narrow cores and broad wings (see Fig. 3), but because of the low signal-to-noise ratio of our echelle spectrum we are only able to measure the total intensity of each emission line. In view of the obvious strength of the stellar absorption lines from the underlying galaxy in PKS 1718−65, we took the additional step of subtracting a scaled version of a 1.5 Å resolution spectrum of the elliptical galaxy NGC 7145 over the critical wavelength range λλ4200–5200 before measuring the Hγ, Hβ, He II λ4686, and [O III] λλ4363, 4959, 5007 line strengths. However, for emission lines as strong as those in PKS 1718−65, the differences between the line intensities measured after such continuum subtraction and those obtained when no such correction is made are relatively small.

The final emission-line intensity measurements are given in Table 3. The relative strengths agree reasonably well with the lower dispersion results of Fosbury *et al.* (1977), although the Hβ flux we measured from a low-dispersion wide-slit observation is a factor of 3 smaller than that found by those authors. The [O III] λ4363 line is very strong, so that the λ4363/λ5007

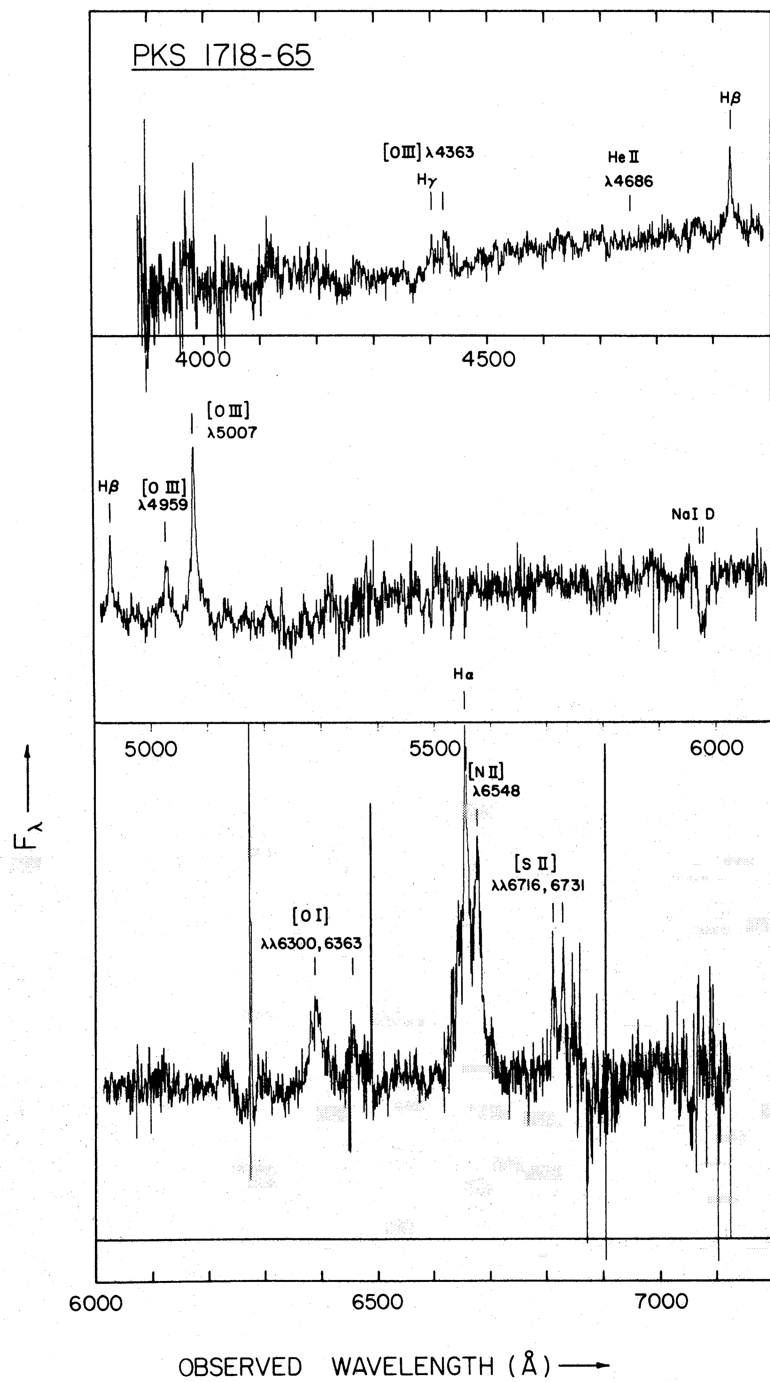

FIG. 3.—Echelle spectrum of PKS 1718 − 65

intensity ratio again points to high electron density. Figure 4 shows a low-resolution spectrum (see Table 1) that confirms the great strength of λ4363.

Of the other emission-line profiles, the most anomalous is that of [O I] λ6300, which is apparently dominated by a broad component of emission that closely matches the wings of the [O III] λλ4959, 5007 and Hβ profiles, but with little or no corresponding emission in a narrow core. The large relative strength of [O I] λ6300 in the broad component is consistent with this emission having its origin in a high-density zone, since this line has a remarkably high critical density.

The emission lines covered by the echelle data have relative intensities similar to those of the broader component in the spectrum of Pictor A, except that λ4363 is even stronger and the [N II] lines are also somewhat stronger. In addition, the lower resolution data show the λ3727/λ5007 ratio to be large, like that in the narrow component of Pictor A. The most important difference from Pictor A is that He II λ4686 is not detected, with an upper limit at about half the value predicted by the power-law photoionization models.

Broad Na I D absorption lines are also observed in the spectrum of PKS 1718 − 65. These are comparable in width to

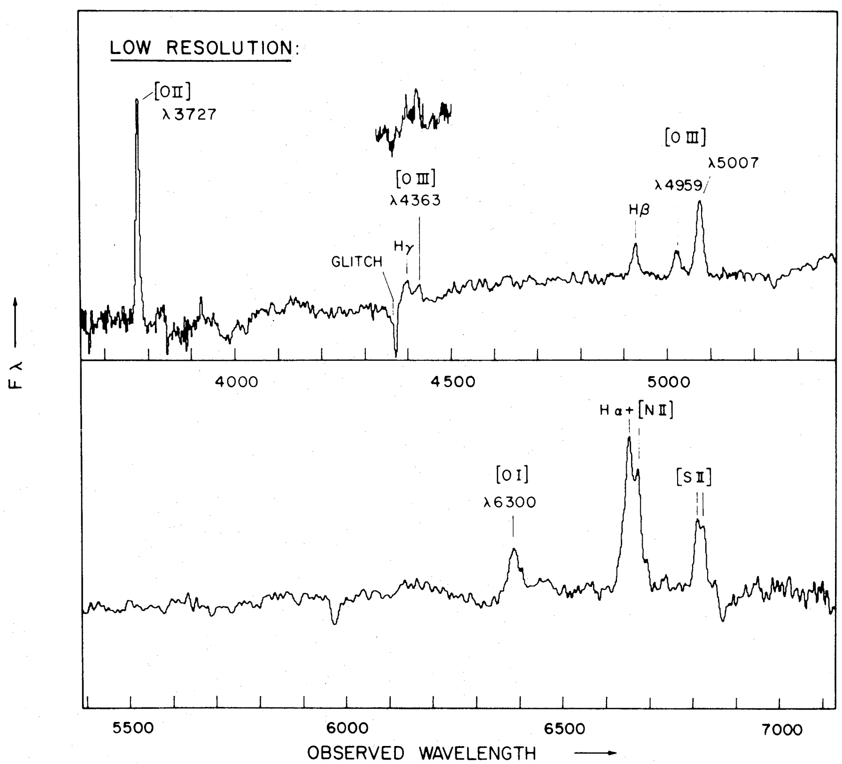

FIG. 4.—Low-resolution SIT Vidicon spectrum of PKS 1718−65. The inset above Hγ and [O III] λ4363 shows these lines at the same scale from the echelle spectrum.

the narrow cores of the emission lines, and are also at the same redshift.

IV. DISCUSSION AND CONCLUSIONS

Pictor A and PKS 1718−65 are examples of Liners that definitely do emit strong [O III] λ4363, but in both cases the λ4363/λ5007 intensity ratio is so high that it is clearly influenced by high electron densities. These lines therefore do not measure the electron temperature in a straightforward way, and cannot distinguish between shock-wave heating and photoionization. However, in the case of Pictor A, we have clearly detected He II λ4686 in the narrow emission-line cores, and perhaps also in the broader wings, at an intensity that strongly favors the power-law photoionization models. Moreover, in our spectra of Pictor A and those of Danziger, Fosbury, and Penston (1977) there is clear evidence for a featureless, nonstellar component of radiation that dominates the optical continuum. When this evidence is considered along with the fact that Pictor A is a strong source of hard X-rays, the most reasonable conclusion is that the Liner in this galaxy is, in fact, photoionized by a power-law-like continuum.

The Liner in PKS 1718−65, like that in the prototype NGC 1052, is much more of an enigma. The weakness of He II λ4686 in these latter two galaxies[3] is inconsistent with the predictions of pure power-law photoionization models of the type calculated by Ferland and Netzer (1982) and Halpern and Steiner (1983) but is quite compatible with the originally suggested mechanism of shock ionization. The λ4686/Hβ ratio places severe limits on the available ionizing flux below the He II ionization edge, while *International Ultraviolet Explorer* (*IUE*) observations of NGC 1052 by Fosbury *et al.* (1981) similarly limit the ionizing flux just to the red of the H I ionization edge. However, Péquignot (1984) has recently shown that photoionization models can still be made to account for the weakness of He II if the ionizing continuum looks like that of a blackbody of temperature $\sim 8 \times 10^4$ K, prolonged by a flat, soft X-ray continuum. Péquignot (1984) further argues that for any photoionization model to successfully explain a Liner such as NGC 1052 (or PKS 1718−65), the gas in the nucleus must be highly stratified, with high-density zones ($> 10^7$ cm^{-3}) nearest the continuum source, and lower density gas ($\sim 10^3$ cm^{-3}) residing further from the center. Interestingly, Filippenko and Halpern (1984) have observed just such a density stratification in the Liner in NGC 7213, and we have seen similar evidence (albeit somewhat less striking) for the same effect in Pictor A and PKS 1718−65.

Theoretical studies have shown that Liner spectra can in principle be produced by a variety of mechanisms. Our observations show that Pictor A is very likely photoionized by a typical power-law-like continuum source, but that a similar continuum source could not by itself account for the ionization conditions in PKS 1718−65. Therefore, the excitation conditions in Liners are produced by, at minimum, a very wide range of photoionizing continuum shapes. Whether this mixed bag includes shock-wave heating is still unclear.

[3] From Fig. 2 of Rose and Tripicco (1983), we estimate λ4686/Hβ ≤ 0.05 in NGC 1052.

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